Status and commissioning plans, the RF system

P. Baudrenghien, with contributions from

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Outline

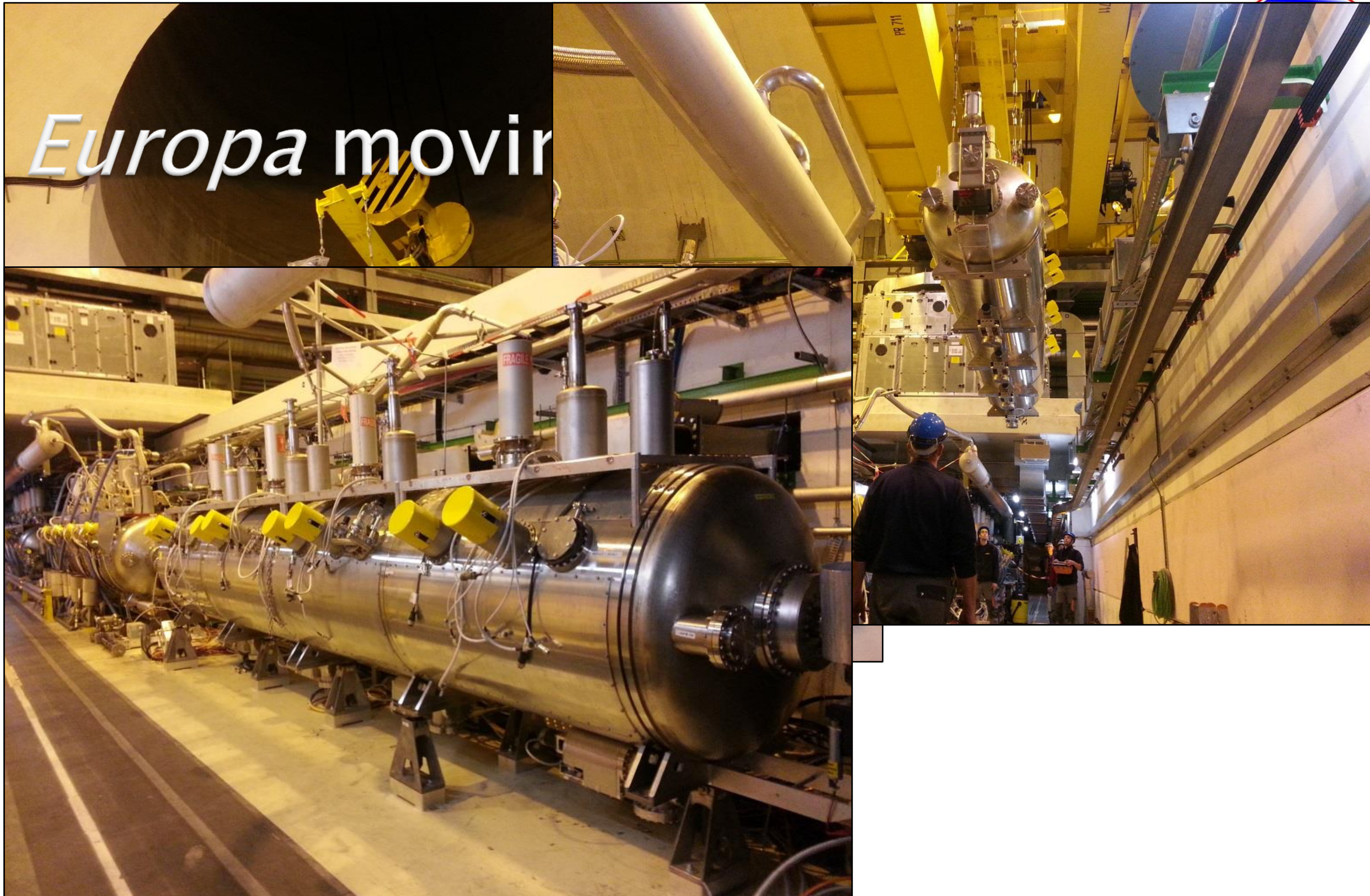
- Upgrades done during LS1
- RF parameters (HW perspective)
- Re-commissioning plans
- A first look at MDs
- Conclusions

Upgrades done during LS1

America coming out…

- The LHC RF design called for 16 MV at 7 TeV, providing for an 8.7 eVs bucket area (2.5 eVs longitudinal emittance, 1ns long bunches)
- At 3.5 and 4 TeV we have operated with 12 MV maximum (1.2 MV in C3B2 and 1.54 MV in the other B2 cavities, 1.5 MV per cavity B1)
- C3B2 could not be operated reliably above 1.2 MV
- Higher voltage may help at 6.5 TeV
- Unequal voltages result in unequal transient beam loading phase slip. A problem for the future RF phase n

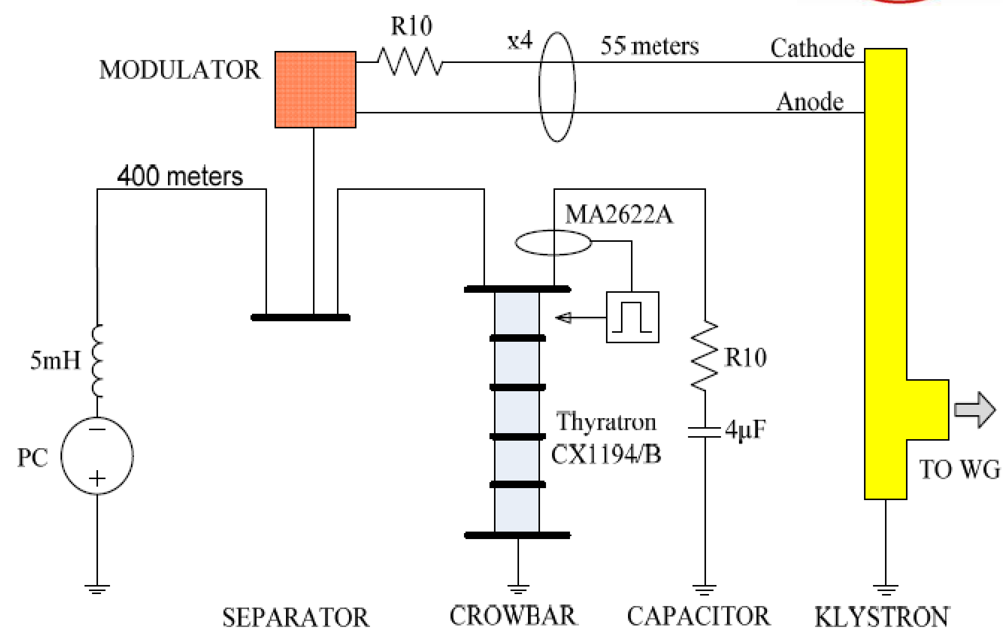
Decision taken to replace the faulty RF module



P. Maesen, G. Pechaud, M. Gourrage, M. Therasse, EN/HE
Photos courtesy of G. Pechaud and M. Gourragne

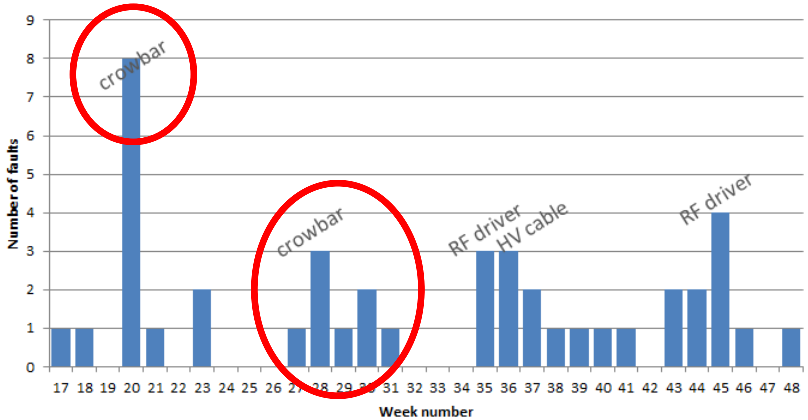
Crowbar protection for klystron

- The current transformer (MA2622A) detects the current spike provoked by an arc in the klystron tube
- It triggers the thyratron that grounds the high voltage on the klystron side



G. Ravida et al., Performance of the Crowbar of the LHC High Power RF System, IPAC 2012

Crowbar replacement



Fault summary year 2012
(from Evian workshop 2012)

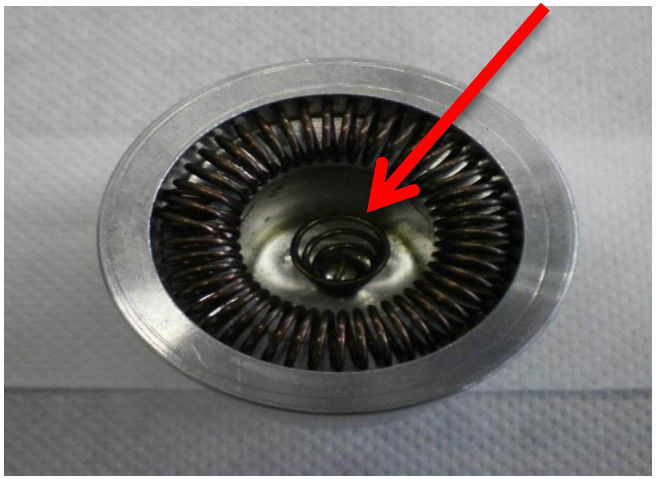
- Solid State device has better performance than the thyratron
- One new system installed in Sept 2012. Validated during 2012-2013 running period

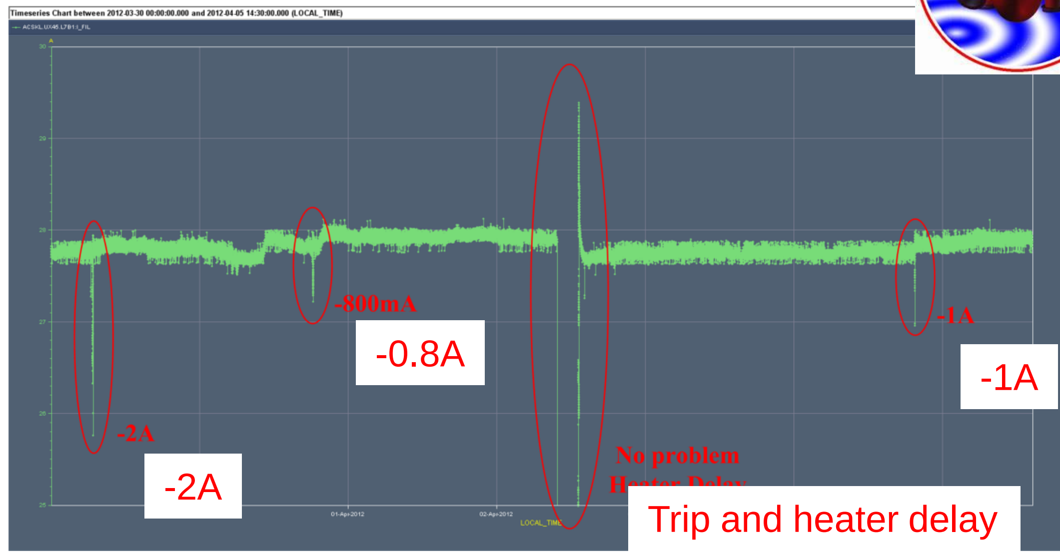
Thyratron (old system)
- Sophisticate circuit
- Water/oil Cooling
- 350 litters oil volume
- Limited lifetime

Solid State thyristor (new system)
- Very simple circuit
- No cooling (±10W)
- 90 litters oil volume

Thyratrons replaced on all 4 Power Converters before restart

"Klystron filament current too low" fault

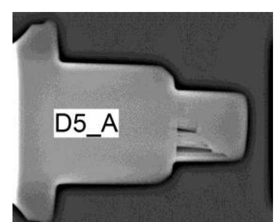




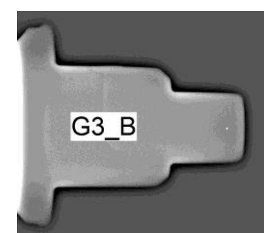
- Klystron filament glitches responsible for frequent RF trips during operation
- HV connectors are responsible. Spring contact degraded
- All replaced. Procedure validated to re-weld the connectors without damaging the insulation material (induction welding)

G. Ravida, P. Martinez Yanez, S. Menoni, C. Nicou, D. Landre, D. Glenat

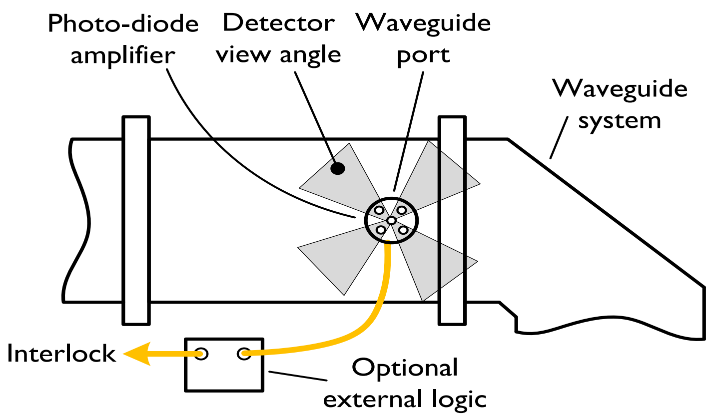
Before

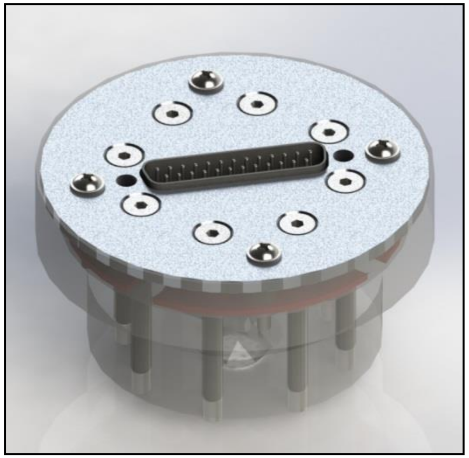


After



New arc detector (waveguide)





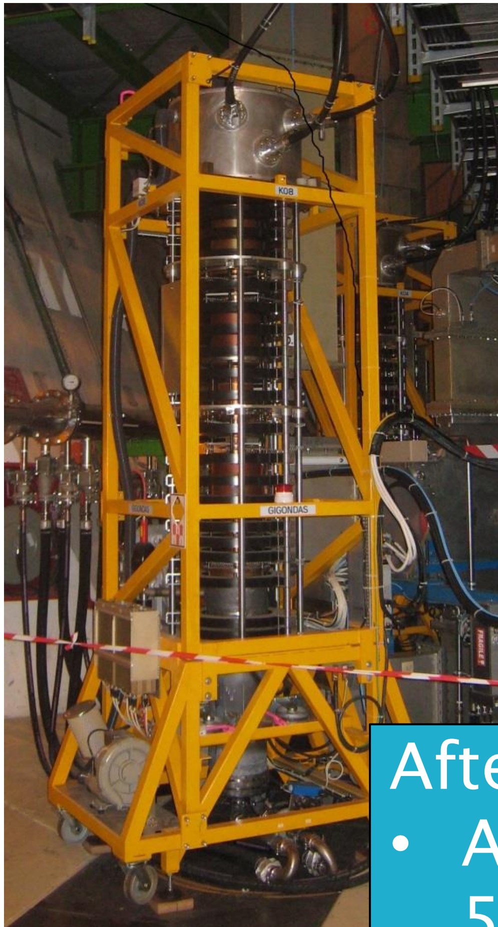
- False alarms from Arc detectors was a big problem in 2010. "*Much problems when increasing beam current. False alarms. Solved by ANDing the detectors by pair*" Evian 2010
- But again in Evian 2011…"*9 Arc Detector false alarm. None after modificatio*

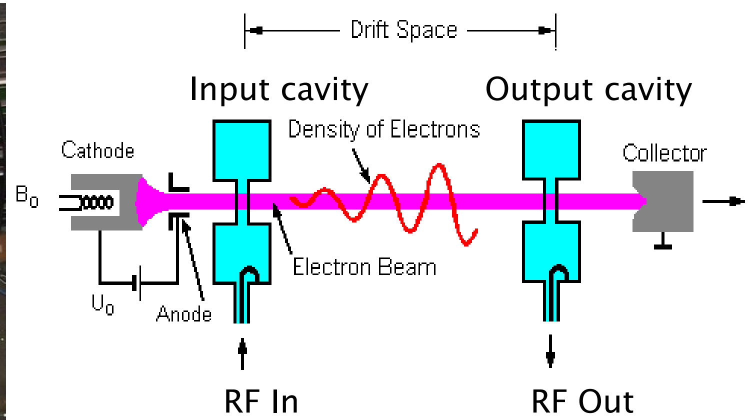
D. Valuch

After LS1:

- New design more resistant to radiation
- Know-how passed to an external company. A commercial product is available for future machines

500 kW klystron collector





- The LHC klystrons are specified for 500 kW DC power (58 kV x 9 A DC)
- After first few weeks of operation in 2009 , the collectors showed marks of over-heating

After LS1:

- All collectors have now been upgraded to 500 kW DC
- In addition we have installed 8 spare klystrons and removed 8 operational klystrons for a better aging profile

RF Controls

- Replacement of CPUs and move to Linux:
  - all RIO3 (LynxOS) will be replaced by MEN A20 (Linux)
  - ~90% of FESA classes already migrated
- FESA upgrade:
  - will start up LHC with new ADT system in FESA3
  - other systems will remain on FESA 2.10
  - port to FESA3 during 2015
- Expert LabView applications:
  - either: will be progressively migrated to RDA 3 and LSA by EN-ICE
  - or: progressively re-implemented using another tool (Inspector?)
- Expert MATLAB applications for commissioning:
  - RDA communications will need migration to RDA3 or JAPC

A. Butterworth, M.Jaussi

New diagnostic: Bunch-by-bunch phase measurement

- The LLRF measures the phase of each bunch individually, then averages over the beam to correct the phase of the RF drive
- Individual bunch phase measurements have been used in the study of electron clouds. It gives information on the energy loss for each bunch

J.E. Muller

- Individual bunch phase observations may become extremely important if we suffer from longitudinal coupled-bunch instability with high intensity 25 ns operation

After LS1

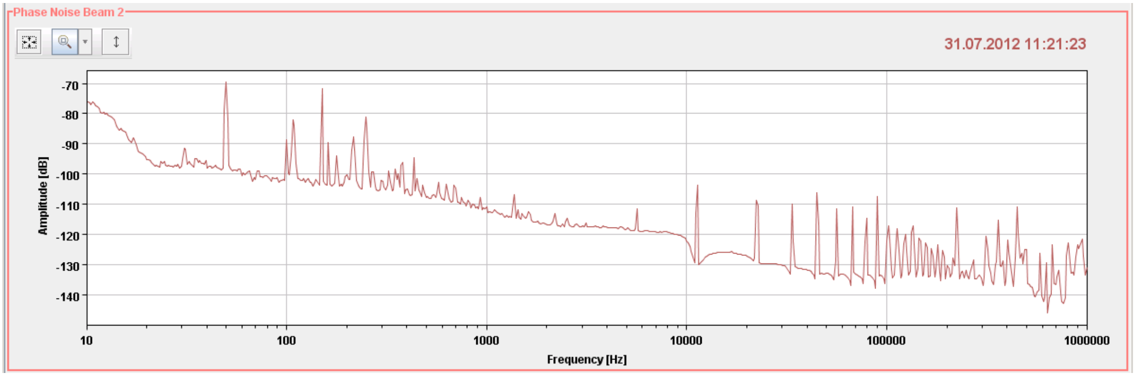
- We will export a stream of single bunch phase measurements @ 40 MSPS, from the VME module
- The logging facility is being finalized and will be similar to the solution used for transverse measurements (ADT)
- It will be linked to the instability trigger
- Help from OP expected to design a CCC application

G.H.H

RF noise monitoring (1)

- RF noise was a major concern during the design of the LHC
- Opinions were aired that it would limit the luminosity lifetime
- This is not the case
- But, on a few occasions, malfunctioning LLRF has resulted in severe RF noise
- The consequence is debunching and population of the abort gap. A concern for Machine Protection

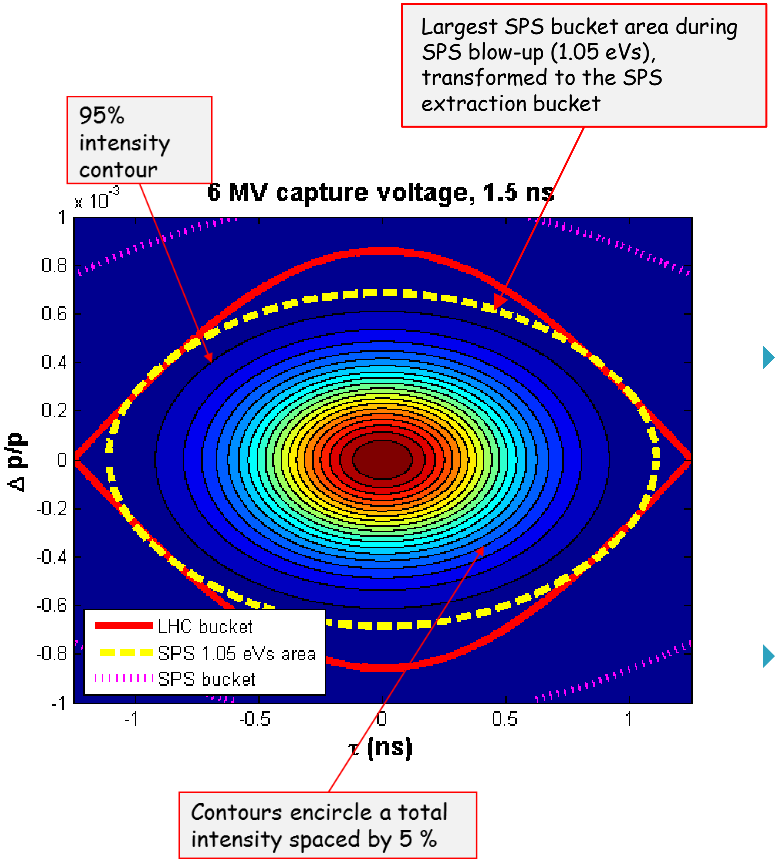
RF noise monitoring (2)



- Run1: a commercial instrument measures the Phase Noise Power Spectral Density (Sum of the 8 cavities, each beam), displays in CCC, compares to reference and generates audio messages
- After LS1(mid 2015)
  - We will have a measurement of the amplitude and phase noise PSD for each cavity
  - It will be implemented in one of our custom-design VME module, and be easily linked to the Control system (display in CCC, logging,…), interlock and even beam-dump-trigger if needed
  - It will ease diagnostic by identifying the faulty cavity

RF parameters

Capture voltage



- We have large statistics on the SPS longitudinal emittance and bunch length (mean) from the 2012 run, with both Q26 and Q20 optics (Oct-Dec). All with 50 ns spacing

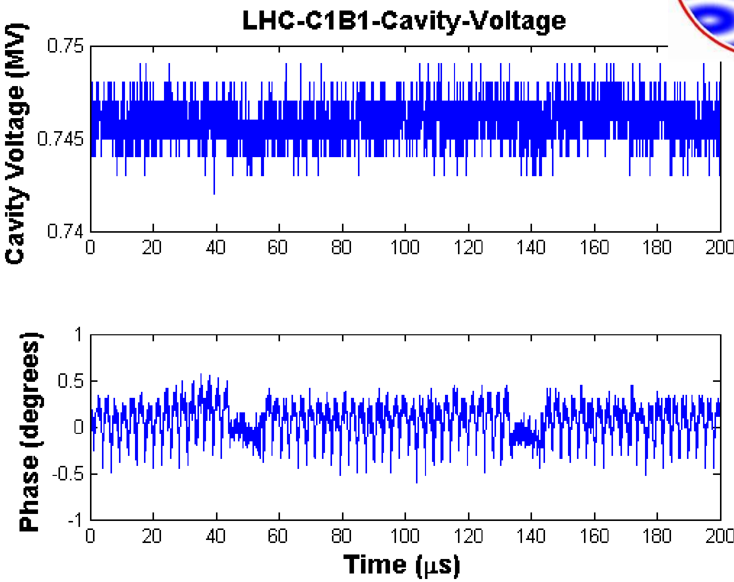
	Long. emittance mean	4σ bunch length mean
Q26	0.5 eVs	1.45 ns
Q20	0.45 eVs	1.6 ns

T. Bohl

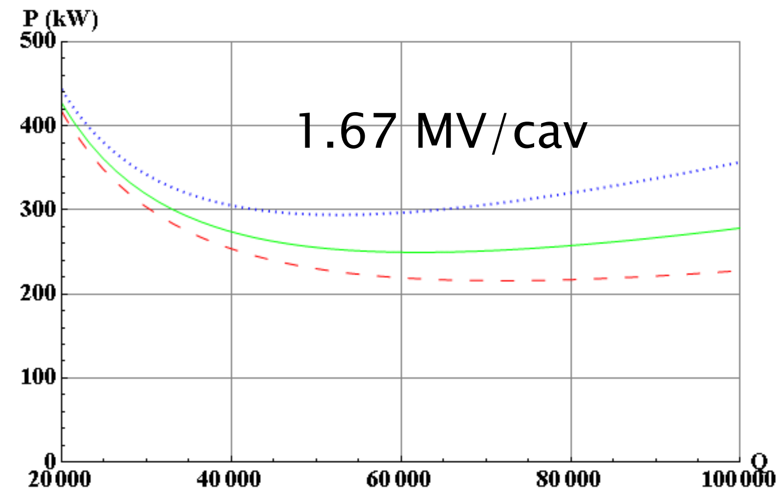
- Measurements are similar for the two optics. The RF capture was therefore kept at 6 MV through 2012.This gives a 1.24 eVs LHC bucket. The measured capture losses in 2012 have been below 0.5 %
- With 25 ns spacing, the bunch intensity will be lower (1.1E11 p vs. 1.4E11-1.65E11 p) but the total current higher (0.55A DC vs. 0.35 A DC). So we do not expect lower longitudinal emittances and bunch length from the SPS and propose to start with 6 MV capture voltage.

Required RF power

- We keep the voltage constant during beam and no-beam segment and detune the cavity so that the demanded klystron power is equal in both cases. That minimizes the peak demanded klystron power
- The power then depends on V, $I_{rf,pk}$ (RF component of beam current during beam segment) and cavity loaded Q_L
- We consider the nominal LHC beam: 1.1E11 p/bunch, 2808 bunches, 0.55 ADC. The RF component of beam current depends on the bunch length and profile



Opposite: Power versus QL for 1.67 MV/cav, 1.25 ns long bunches, cosine square (fb=0.837), gaussian (fb=0.715). Point-like bunches (fb=1)



- The Q_L can be optimized giving the minimal required power

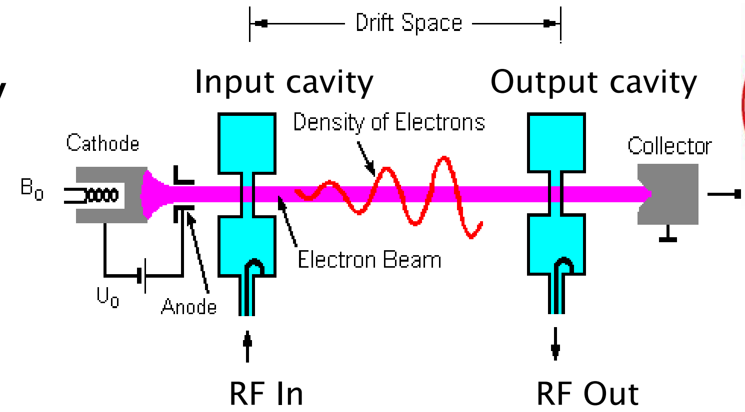
$$P = \frac{V\ I_{rf,pk}}{8}$$

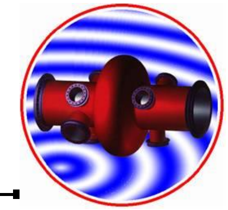
- Each LHC klystron can provide 300 kW RF. We keep a 20% margin for regulation, therefore limiting the theoretical power at 250 kW. This sets the maximum voltage per cavity

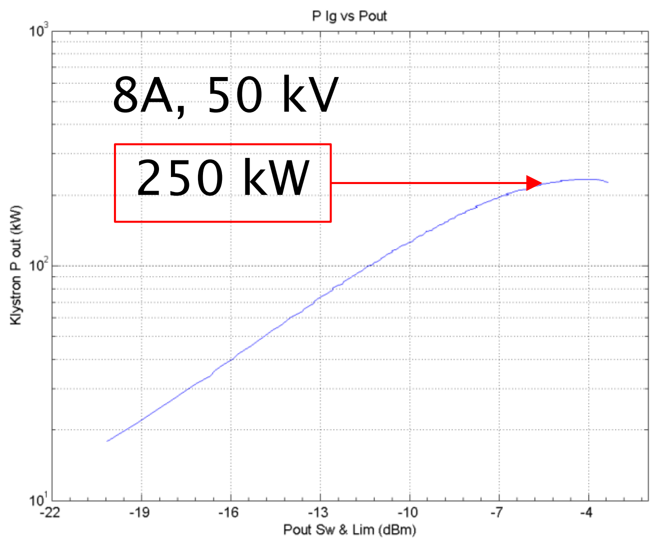
		Gaussian		Cosine2		Point-like	
I_{DC}	Bunch length	$I_{rf,pk}$	V @ 250 kW (MV)	$I_{rf,pk}$	V @ 250 kW (MV)	$I_{rf,pk}$	V @ 250 kW (MV)
0.55 A DC	1ns 4σ	1.156	1.73	1.269	1.58	1.41	1.42
	1.25 ns 4σ	1.034	1.93	1.196	1.67	1.41	1.42
0.50 A DC	1ns 4σ	1.04	1.92	1.142	1.75	1.269	1.58
	1.25 ns 4σ	0.931	2.15	1.076	1.86	1.269	1.58

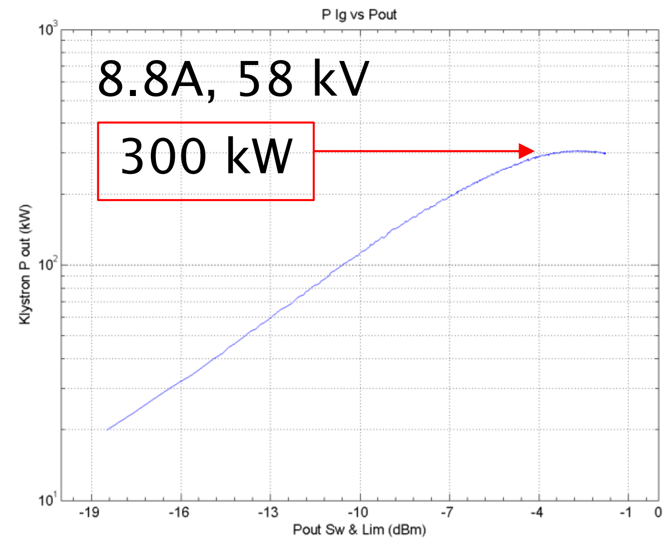
- Taking the cosine^2.profile, with the 8 cavities we can get 12.6 MV (1ns) or 13.4 MV (1.25 ns)
- With 0.5 A DC, we have 14 MV (1 ns) or 14.9 MV (1.25 ns)

- The power available from the LHC klystron can be changed by modifying its DC settings: Cathode Current and Anode Voltage









- We could operate the klystrons at low DC settings during filling where 120 kW are sufficient
- Move to high-power settings before start ramp. Procedure tested during run 1.

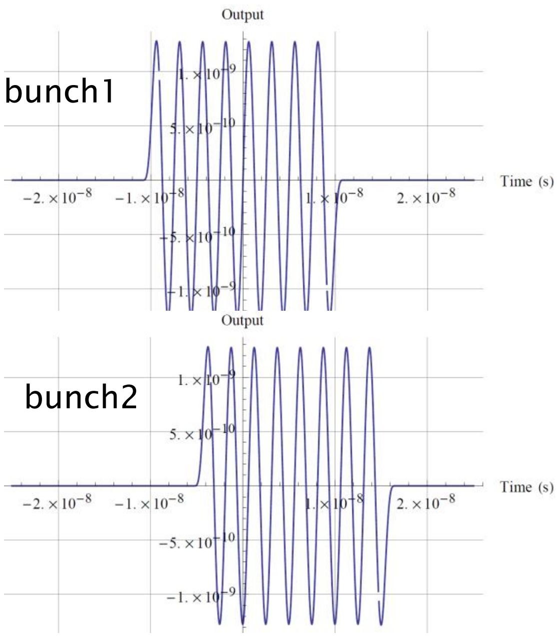
Bunch spacing

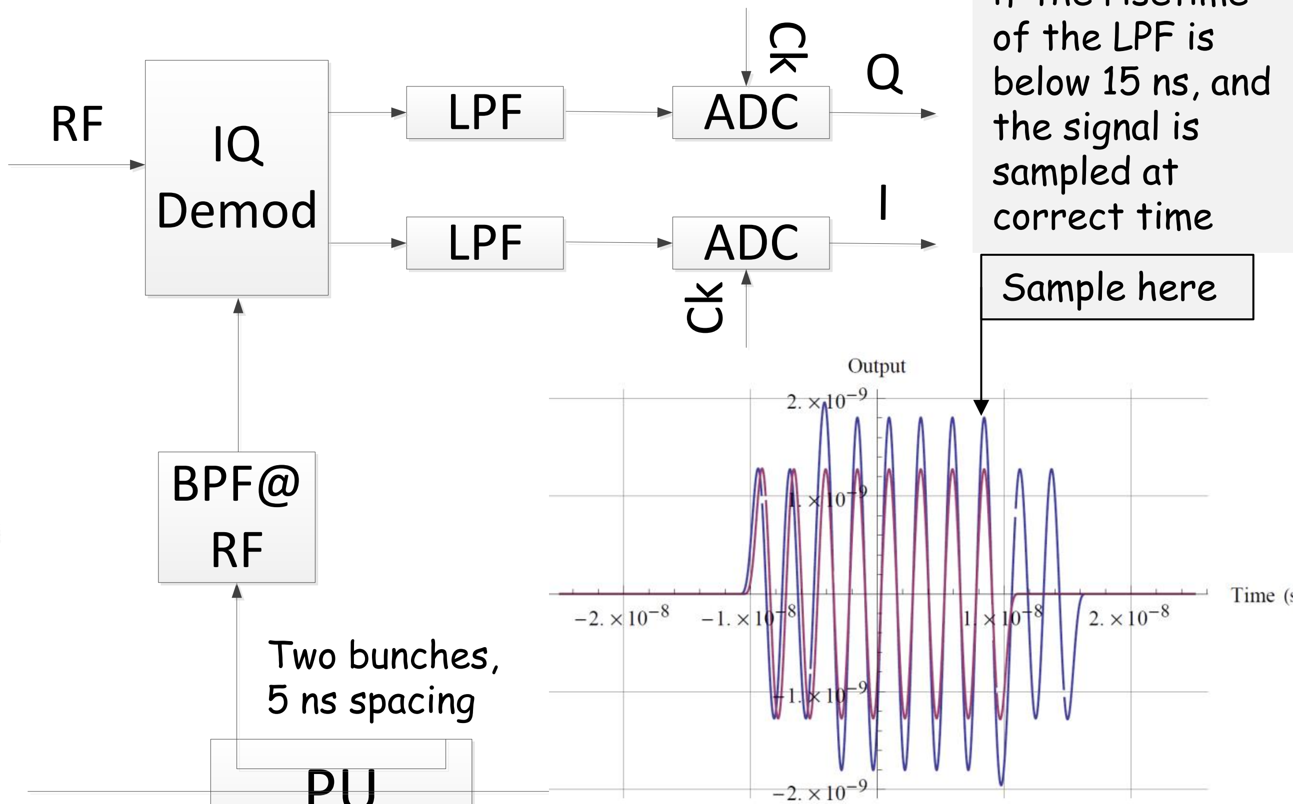
- The LHC RF is a single-frequency system at 400 MHz and can therefore deal with bunches spaced by multiples of 2.5 ns
- The fast local loop controlling the cavity field, located in UX45 is clocked at 40 MSPS but it does not use beam signal. It will work with any bunch pattern.
- The beam control in SR4 uses PU signal and will be affected by the bunch pattern.
- The only part affected is the Beam Phase Loop. It is designed for bunches spaced by multiple of 25 ns
  - With 25 ns sp
    bunch individu
  - Then we avera
  - The result upd

- The RF was designed for 25 ns spacing. No problem
- With 5 ns -20 ns spacing (scrubbing beams) the Beam Phase loop will perform differently

5 + 20 ns spacing

Passage of a bunch in the PU generates a 20 ns long wavelet @ 400 MHz





The measurement correctly averages over the two bunches if the risetime of the LPF is below 15 ns, and the signal is sampled at correct time

Sample here

- The phase measurements, every 25 ns, will correctly average over the two bunches. (LBOC Nov 26th,2013 for more)

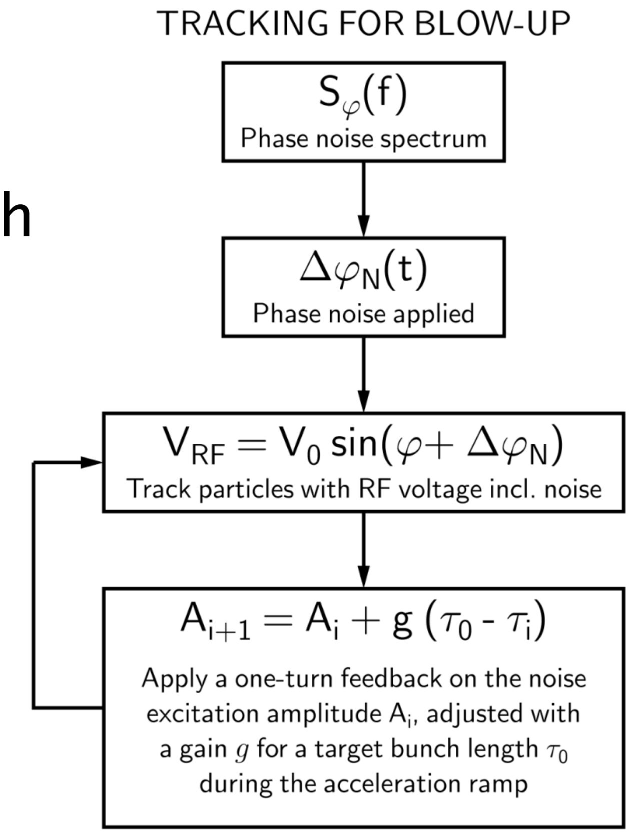
Shaping the longitudinal distribution with RF phase noise

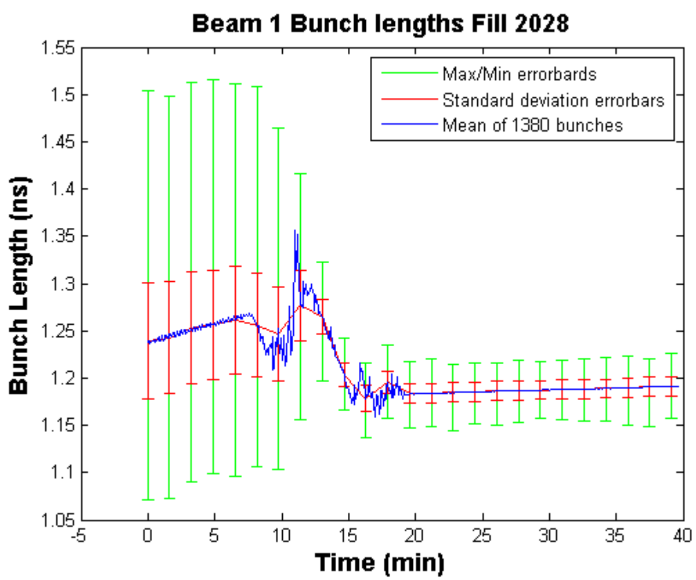
- Controlled injection of RF phase noise
  - Is used to increase longitudinal stability via blow-up (increase of the longitudinal emittance)
  - Can be used to shape the bunch according to the noise spectrum, for example for the production of flat bunches (longitudinal flat profile)
  - May be needed to compensate the synchrotron radiation damping in physics
- Many data available from run1. Several observation are not understood
- A simulation code is being implemented into PyHEADTAIL

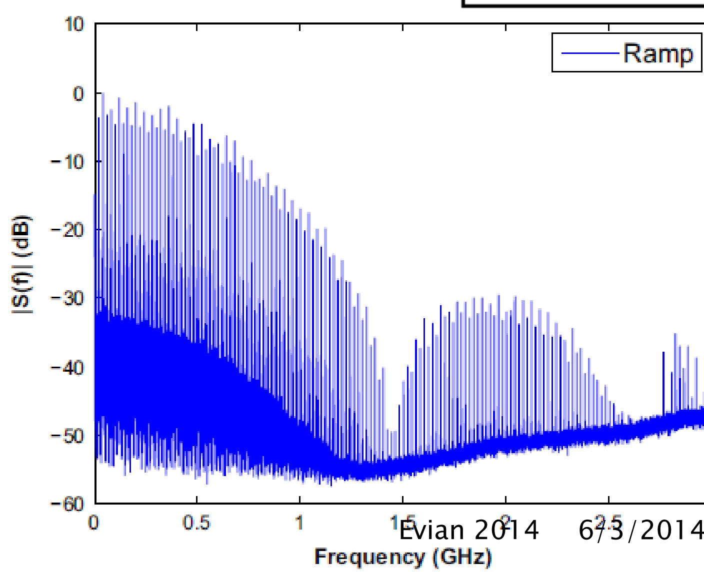
H. Timko

Longitudinal blow-up

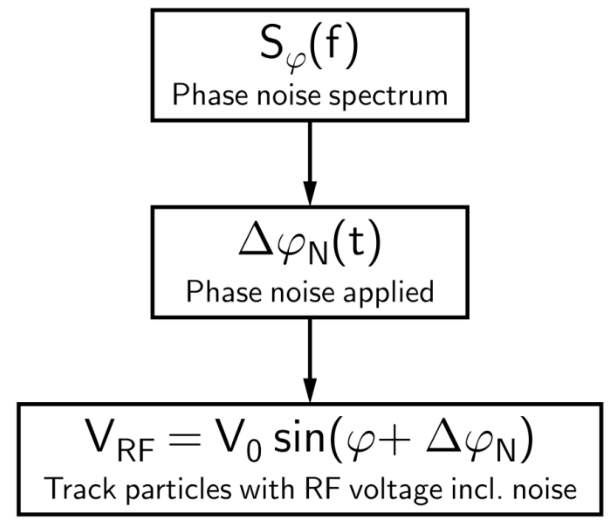
- For the blow-up, the first goal is to reproduce the run 1 measurements with the simulations
- Then the phase noise spectrum could be optimized, to make blow-up more regular, or to produce longitudinal profiles that create less heating, for example





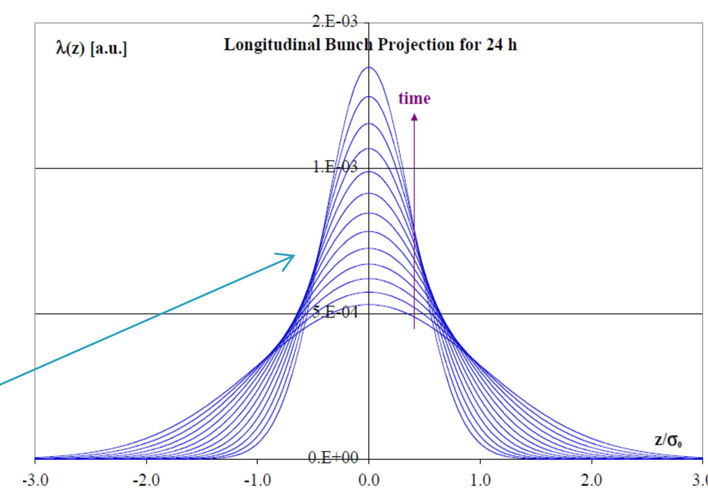


TRACKING FOR BUNCH SHAPING



Flat or longer bunches

- Studies ongoing to find an optimum noise spectrum for a targeted bunch profile
  - Could be used in physics to flatten (shape) the bunches
  - Reduction of beam-induced heating
  - Flat bunch could be beneficial for transverse stability and luminosity
- Ignoring all other blow-up sources, at 7 TeV, the bunch length shrinks to 80% of its initial value in 6 h (24 h damping time in σ_z)



Reproduced from J. Tuckmantel, LHC Project Report 819, *Synchrotron Radiation Damping in LHC and Longitudinal Bunch Shape*, 2005

Plans for re-commissioning

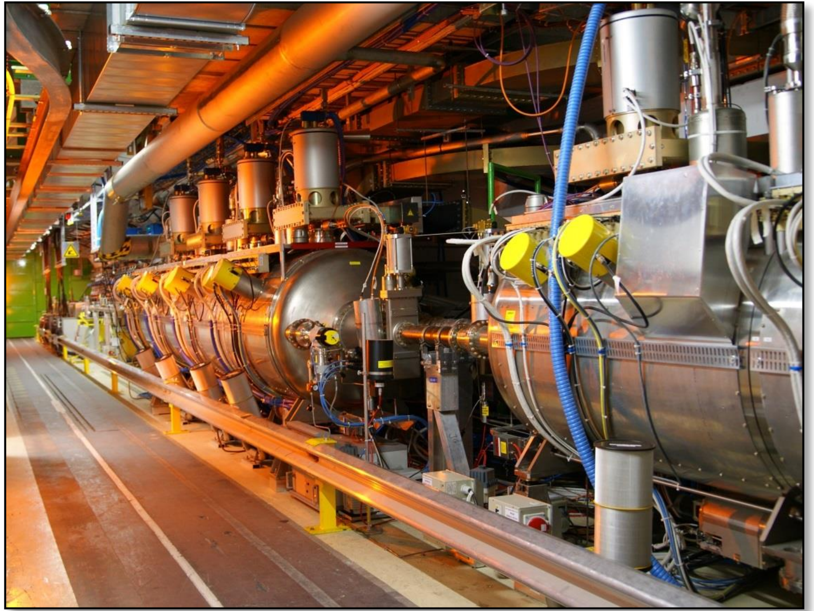
Step 1: Re-commission the High-Voltage

- Goal: re-commission the HV (50-60 kV) for the klystrons
- To be done: test of interlocks, commissioning the new crow-bars
- Start and duration: 2 weeks, can start in September
- Pre-conditions: general services (240/400 V), demineralized water, access to UX45 (incompatible with magnet ramping), 18 kV, power converters operational (including controls), controls software operational for the RF equipment in the HV bunkers (FESA, expert tools).

Step 2: Re-commission the High-Power RF

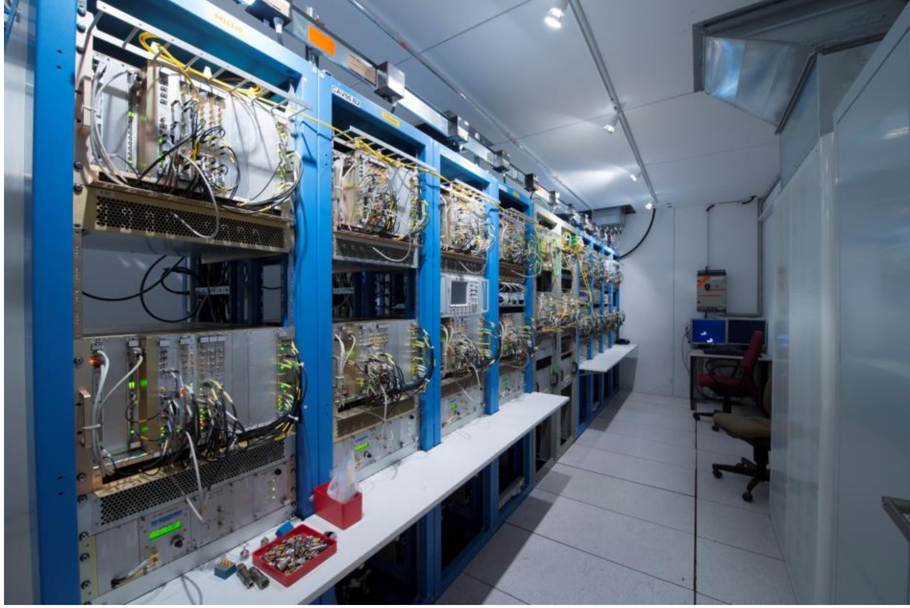
- Goal: re-commission the klystrons with waveguides on short-circuits. 8 new klystrons installed
- To be done: test of interlocks, commissioning the klystrons, calibrations
- Start and duration: 2 weeks, can start in October
- Pre-conditions: in addition to the previous conditions, controls software operational for the High power equipment (FESA, expert tools), part of LLRF operational (SwLim module, RF drive interlock).

Step 3: Re-commission the cavities



- Goal: re-commission the cavities. One new module (4 cavities) has been installed during LS1
- To be done: test of interlocks, conditioning of cavities, calibrations
- Start and duration: 3 weeks, cannot start before cryo ready (Nov.?)
- Pre-conditions: in addition to the previous conditions, cryo OK in sectors 34 and 45 (modules full and cold, stable conditions), RF zone closed (work may require occasional access to the tunnel), controls software operational for the cavities (FESA, expert tools), part of LLRF operational (conditioning mode), CCC RF-Control software operational (LSA-functions , RF Control application).

Step 4: Re-commission the LLRF



- Goal: re-commission the tuning and feedback loops
- To be done: calibration of cavity Q_L vs. coupler position, optimization of parameters for the LLRF
- Start and duration: 2-3 weeks, can start as soon as some cavities are conditioned to 2 MV
- Pre-conditions: in addition to the previous conditions, all controls software operational for the LLRF (FESA, expert tools).

A first look at MDs

First MDs

- Loss of Landau damping. What is the minimal stable longitudinal emittance at 6.5 TeV? We have rescaled results from MDs at 4 TeV (J.E. Muller's talk). These should be confirmed at 6.5 TeV. This will set the minimum RF voltage at 6.5 TeV
- Few ramps with moderate intensities and different flat top voltages. Observe longitudinal evolutions during few hours. Single beam first, then in collision
- Shaping the longitudinal bunch profile by injection of colored RF phase noise or using sinusoidal phase modulation (guided by results of PyHEADTAIL simulations)
- Improvements to the longitudinal blow-up (effect of phase loop). This will also benefit from the PyHEADTAIL simulations

Conclusions

Conclusions (1/2)

- **HLRF**. Large-scale modifications: New module, new crowbars, klystrons upgraded for full DC power. All ready for start-up
- **RF voltage:**
  - Capture with 6 MV (as in 2011-2012)
  - The maximum RF voltage is 13.4 MV (0.55 A DC) and 14.9 MV (0.5 A DC), assuming cosine^2 profile, 1.25 ns base
  - Operation with 250 kW+ RF power requires the 8.8A/58 kV klystron DC settings. These could be reduced during filling and preparation
  - Collision with a lower voltage may be interesting at the beginning of physics as it reduces the momentum spread. It has a negative impact on IBS though.

Conclusions (2/2)

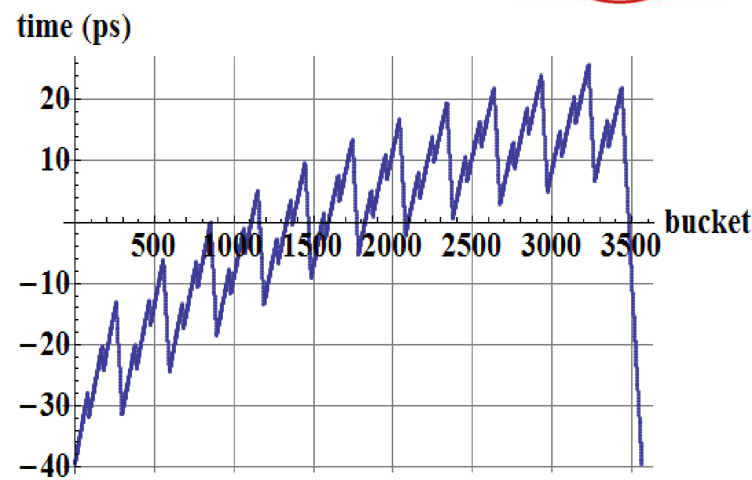
- **Exotic bunch spacing:** With a minor adjustment the RF will cope with the 5-20 ns bunch spacing
- **New diagnostics** are in preparation: bunch-by-bunch phase measurement (hopefully available at start-up), monitoring of the RF noise (second half 2015)
- The injection of RF phase noise is being implemented in the **PyHEADTAIL** simulation code. The goal is to improve longitudinal blow-up and control bunch profile in physics.

- Thank you for your attention

Back-up slides

Other planned LLRF improvements

- A longitudinal damper, acting via the ACS cavities, would reduce the capture losses at injection. A first MD was conducted in 2013. Work will continue during and after LS1
- The RF voltage phase modulation along the beam batch will be essential in the HiLumi era (above ~0.6 A DC). Several MDs in 2012 have given good results. Incompatibility with the 1-T feedback must be understood. Work will continue after LS1



Modulation of the cavity phase by the transient beam loading in physics. 2835 bunches, 1.7 1011 p/bunch, 1.5 MV/cavity, QL=60k, full detuning (-7.8 kHz).